Beryllium in the Hyades F and G Dwarfs from Keck/HIRES Spectra

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ABSTRACT

Although there are extensive observations of Li in field stars of all types and in both open and (recently) globular cluster stars, there are relatively few observations of Be. Because Be is not destroyed as easily as Li, the abundances of Li and Be together can tell us more about the internal physical processes in stars than either element can alone. We have obtained high-resolution (45,000) and high signal-to-noise (typically 90 per pixel) spectra of the Be II resonance lines in 34 Hyades F and G dwarfs with the Keck I telescope and HIRES. In addition we took a spectrum of the daytime sky to use as a surrogate for the solar spectrum so we could determine the value for Be in the sun - analyzed in the same manner as that for the stars. We have adopted the stellar temperatures and some of the Li abundances for these stars from the literature. For most of the F dwarfs we have rederived Li abundances. The Be abundances have been derived with the spectrum synthesis method. We find that Be is depleted, but detected, in the Li gap in the F stars reaching down to values of A(Be) = 0.60, or a factor of nearly seven below the meteoritic Be abundance (a factor of 3.5 below the solar value of Chmielewski et al.). There is little or no depletion of Be in stars cooler than 6000 K, in spite of the large depletions (0.5 - 2.5 dex) in Li. The mean value of A(Be) for the ten coolest stars is 1.33 $\pm$0.06, not far from the meteoritic value of 1.42. The pattern in the Be abundances – a Be dip and undepleted Be in the cool stars – is well matched by the predictions of slow mixing due to stellar rotation. We have interpolated the calculations of Deliyannis and Pinsonneault for Be depletion due to rotational mixing

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to the age of the Hyades; we find excellent agreement of the predictions with the observed Be abundances but less good agreement with the observed Li abundances. Some of our Hyades stars have photometrically-determined rotation periods, but there is no relation between Be and rotation period. (Generally, the lower mass stars have lower Li and longer periods which may indicate greater spin-down and thus more Li depletion relative to Be.) The Li and Be abundances are correlated for stars in the temperature range of 5850 - 6680 K, similar to results from earlier work on Li and Be in F and G field stars. This indicates that the depletions are not just correlated - as is the only thing that can be claimed for the field stars - but are probably occurring together during main-sequence evolution. The Hyades G dwarfs have more Be than the sun; their initial Be may have been larger or they may not be old enough to have depleted much Be. For those Hyades stars which appear to have little or no depletion of Li or Be, the Li/Be ratio is found to be 75 $\pm$30; the meteoritic ratio Li/Be is 78. The Hyades ratio is a representative value for the initial ratio in the material out of which the Hyades cluster was formed.

1. Introduction

The abundance of Li is known for a large number of F and G dwarfs in the field and in open clusters. The Li information from clusters of different ages and metallicities is particularly useful in ascertaining the mechanisms that may lead to the surface depletion of Li. However, the standard, non-rotating, evolutionary models of F and G dwarfs are not sufficient to explain the observed abundances in clusters of the Hyades age and older (e.g. Jones et al. 1999). One can see the effect of age in the distribution of A(Li) with temperature in stars in clusters of a range in age. (Here we use A(X) = log N(X)/N(H) + 12.00.) For clusters the distribution of A(Li) with temperature is the equivalent of the distribution with mass. There is a clear discussion of the Li abundances in clusters of different ages in Deliyannis (2000). Metallicity is another parameter that affects Li depletion; the surface convection zone is deeper in the metal-rich stars (at the same mass) and surface Li would thus have the potential to be depleted more in stars in the metal-rich clusters.

In contrast with Li, there is relatively little information on the Be abundances, especially in G stars, *both* in clusters and in the field. The major reason for the relatively few Be observations is that Be is observed through the resonance lines of Be II at 3130.421 and 3131.065 Å, a spectral region not nearly as accessible to ground-based telescopes as the Li I region near 6707 Å. Atoms of Li are destroyed by fusion with protons at internal stellar temperatures of $\sim$2.5 x 10^6 K, while those of Be are destroyed at $\sim$ 3.5 x 10^6 K, i.e. Be survives to greater depths than does Li. Therefore, information on the abundances of the two elements together provides far more powerful indicators for the building of model stars and for learning about the probable causes of light element depletion. In Boesgaard et al. (2001) we have derived Be abundances for 46 F and G field stars and compared them with Li abundances in the same stars. The most notable result from this is the correlation

between A(Li) and A(Be) for stars with T_{eff} between about 5850 and 6680 K.

It is especially useful to observe Be in clusters because the stars have a common (known) age and metallicity and (presumably a common initial abundance of Li and Be), thus two parameters are removed from the study, compared to the usual mix of field stars. However, there are almost no observations of Be in open cluster stars.

We present a summary here. F Dwarfs: In 1986 Boesgaard & Tripicco (1986) discovered that Hyades stars had severely depleted Li in a narrow temperature range, 6300 - 6850 K, the "Li gap." Boesgaard & Budge (1989) then derived Be abundances for eight Hyades F dwarfs in the Hyades Li gap region. They found that while there was not a dramatic drop in Be (as there is in Li), they could not rule out a drop of a factor of 2-4 across the Li gap.

G Dwarfs: The Li abundances in G dwarfs in the Hyades decrease by about three orders of magnitude from T_{eff} = 6000 K to 5000 K (Cayrel et al. 1984, Soderblom et al. 1990, Thorburn et al. 1993). Four of these Hyades G dwarfs were observed for Be by by García López, Rebolo & Pérez de Taoro (1995). Although they had low signal-to-noise (S/N) spectra (15-20), they were able to show that Be did not decrease in abundance over this large drop in Li. They also observed three stars in the Ursa Major Group, but could only determine upper limits on the Be abundance for them.

Here we report on new Keck/HIRES observations of Be in the Hyades. We have determined Be abundances for 34 Hyades dwarfs with known Li abundances distributed over a temperature range of 5400 - 7400 K, both F and G dwarfs.

2. Data Acquisition and Reduction

The Hyades spectra were obtained over four nights: 1999 November 13-15 (UT) and 2001 February 1 (UT) with the Keck I 10-m telescope and the HIRES echelle spectrograph (Vogt et al. 1994) with a Tektronix 2048×2048 CCD. Because the Be II lines are near the atmospheric cut-off, we take Be spectra at low airmass, near the meridian, to obtain high signal-to-noise (S/N) ratios. However, during the February 2001 run, the upper dome shutter could not be opened, so all exposures were at least one hour from the meridian to avoid obscuration of the telescope mirror by the dome. The 15 μm pixels of the HIRES CCD and the $0.86''$ slit width yielded a measured resolution (from Th-Ar lamp lines) of $\sim$45,000 ($\sim$3.1 pix, FWHM). Exposure times ranged from 7 to 60 minutes, resulting in achieved per pixel S/N values near the λ3131.06 Be II feature of 20-120 (a median of 88 with 80% over 70); this is considerably larger than obtained in the previous study of four Hyades cool, faint stars by García López et al. (1995). Table 1 lists the objects, spectral types, V magnitudes, B-V colors, observation date, exposure time, and S/N ratios per pixel. Examples of the spectra can be seen in Figures 1 and 2. They are arranged a-h in order of decreasing temperature.

Data reduction was carried out using standard routines in the echelle package of IRAF[2]. All frames were first trimmed, overscan-subtracted, and then bias-subtracted using a residual frame formed by medianing together numerous overscan-subtracted bias frames acquired each night. We formed a nightly master flat-field frame by combining numerous processed quartz-lamp frames acquired each night. The orders in this frame were identified and traced using the routine apall. We produced a normalized flat-field by fitting a low order spline to the blaze/lamp functions employing the routine apnormalize.

Object frames were pre-processed in the same fashion, and then divided by the normalized flat-field. We then removed scattered light by fitting low order splines to inter-order regions across the dispersion and then smoothing these along the dispersion direction using the apscatter routine. Pixels in or near the Be order that were afflicted by particle events or cosmetic defects were identified manually and replaced with values based on surrounding pixels using the fixpix routine. Order apertures were interactively identified, defined, traced, and extracted using the apall package. The bluest complete order was skipped due to a dearth of useful signal and concomitant difficulties in reliable tracing. Several of the reddest orders were also skipped due to saturation in the flat-fields– though the unflattened data would still be of comparable quality to that presented here given the intrinsic flatness of the Tektronix CCD. The (complete) wavelength coverage of the final spectra is from 3030 to 3780 Å.

A wavelength scale for our 1-d extracted spectra was determined by fitting 400-550 Th-Ar lamp lines with low order Chebyshev polynomials. The typical rms residuals of these fits were $\lesssim$0.002 Å– about 9% of a single 0.0215 Å pixel. Finally, preliminary continuum normalization of the spectra was carried out in the specialized 1-d spectral analysis SPECTRE (Fitzpatrick & Sneden 1987). The goal of this step was to fit the overall gross morphology (i.e., scaled shape) of the continuum– not the precise absolute level, which was refined and established as part of the spectrum synthesis analysis (§3.2).

3. Abundances

3.1. Stellar Parameters

Lithium has been observed in all of our stars by Boesgaard & Tripicco (1986) (BT), Boesgaard & Budge (1988)(BB), Soderblom et al. (1990), and Thorburn et al. (1993). The temperature scales used in these papers are quite consistent with one another. We adopt the BT and BB temperatures for the stars observed in those papers. All the other stars were observed by Thorburn et al. (1993) and we have adopted those values for the temperatures and for the Li abundances in each star. Table 2 indicates which reference was used for each star.

[2]IRAF is distributed by the National Optical Astronomical Observatories, which are operated by AURA, Inc. under contract to the NSF.

Beryllium abundances are sensitive to log g, so we wish to be sure to have a good relative scale for log g. Consequently we used the simple relation of Gray (1976) for main sequence stars: log g = 4.17 + 0.38(B-V). Thus the relative log g's in the cluster stars are known to the accuracy of the B-V values. For [Fe/H] we adopted +0.13 from Boesgaard (1989) and Boesgaard & Friel (1990). We found values for the microturbulent velocity from the formula of Nissen (1981). Published measurements of v sin i are also listed for those stars studied by Kraft (1965).

The parameters for each star are given in Table 2. Model atmospheres were calculated for each star for its parameters from the Kurucz grid (1993).

3.2. Abundance Analysis

The Be abundances for all of the stars were determined by spectrum synthesis with the program MOOG (Sneden 1973), as modified in February, 1998. We started with the Kurucz line list and looked at the effects of small changes in the gf values for some of the features that blend with the Be lines.

In their analysis of the Be II line at 3131.064 Å , García López et al. (1995) discuss the blending feature of Mn I at λ 3131.037. They altered the log gf value from that given in the Kurucz list from −1.725 to −0.225 to match the solar atlas of Kurucz et al. (1984) to a solar Be abundance of A(Be) = 1.15 (where A(Be) is log N(Be/H) + 12.00) as found by Chmielewski et al. (1975) and Anders & Grevesse (1989). (They used the solar abundance of A(Mn) = 5.39 from Anders & Grevesse.) King et al. (1997) show that the log gf value for the Mn II line at λ 3131.015 needs to be increased by 1.726 dex, the Mn I line strength returned to the original value (−1.725) and the CH line at λ3131.058 dropped altogether to achieve an excellent match to the solar flux atlas of Kurucz et al. (1984). Alternatively, King et al. (1997) keep the CH line and increase the Mn II line gf by 1.62 dex.

In this work we have used the line list that was used in Stephens et al. (1997), Boesgaard et al. (1998) and Deliyannis et al. (1998). The modifications to the Kurucz list are a reduction in the gf value for the CH line at 3131.058 Å to 4.00 x 10^{-3} and an increase in gf for the Mn II line at 3131.015 Å to 4.00 x 10^{-1} (an increase of 0.82 dex). Otherwise the list includes the few cosmetic alterations of the King et al. (1997) list. There are some 190 lines in the 4 Å region surrounding the Be II lines.

We obtained a Keck spectrum of the daytime sky just after sunrise on 7 October, 1993 UT of 20 m duration which has a S/N ratio of 138 per pixel. A spectrum synthesis of this spectrum with the line list that we use here, results in a derived Be abundance for the Sun of A(Be) = 1.15 dex. This is in agreement with the accepted result of Chmielewski et al. (1975) of 1.15 dex. The meteoritic abundance is A(Be) = 1.42 from Anders & Grevesse. We discuss the photospheric vs meteoritic Be abundance in section 4.3.

Examples of the spectrum synthesis fits are shown in Figures 3-5; each figure is a pair of stars – two warm, two intermediate, and two cool – with temperatures that span a total range of 1000 K. The line list used provides very good, but not perfect, matches over this range in temperature. Some of the imperfections in the fits are due to small changes in the slope of the original continuum fitting, especially in the region near 3129.7 Å; the data points seem too high in Figure 3 and too low in Figure 5b. We have relied primarily on the red line of the Be II pair at 3131.065 Å for the abundance determination. Table 2 gives the final Be abundances as A(Be) = log N(Be/H) + 12.00.

We have adopted the Thorburn et al. (1993) Li abundances for 16 stars. (We did run their equivalent widths through MOOG with the Kurucz atmospheres and found that the Li abundances agreed with theirs to within ±0.05 dex.) For the 18 stars of BT and BB we have redetermined the Li abundances as follows. We treated the Li line as a blend of the Li I resonance doublet split by hyperfine interaction and an Fe I line at 6707.411 Å; the atomic data for this are from Andersen, Gustafsson & Lambert (1984). We used the MOOG program in the "blends" mode. The results for A(Li) are also given in Table 2. One star, vB 48, has had its Li determined by four different studies: Boesgaard & Tripicco (BT) (1986), Rebolo & Beckman (RB) (1988), Soderblom et al. (S) (1990), and Thorburn et al. (T) (1993). The temperatures, Li equivalent widths, and Li abundances for this star are as follows: BT: 6246 K, 93 mA, 3.04; RB: 6260 K, 91 mA, 3.00; S: 6200 K, 74 mA, 2.92; T: 6222 K, 91 mA, 3.07. The temperatures are in excellent agreement and with the exception of Soderblom et al. the Li equivalent widths and A(Li) values are also in excellent agreement.

The quoted errors in T_{eff} are ±10 to ±50 K (see the discussion in Thorburn et al. 1993 and BB). This results in an uncertainty in A(Be) of ±0.02 - 0.03 dex. According to Gray's (1976) relation between log g and B-V, the probable error on log g is ±0.075 dex. This translates to an error in A(Be) of ±0.04 dex. The data quality affects the abundance results also, for example the fitting of the continuum is influenced by the S/N ratio. One of the larger sources of uncertainty in the abundance derivation comes from the rotational broadening, especially for stars rotating more than$\sim$18 km s^{-1}. These two parts of the error in A(Be) are evaluated at 0.03 - 0.08 dex, except for the more rapidly rotating vB101 (40 km s^{-1}) for which we assess a total error of ±0.21 dex. Although the stellar parameters are not independent of each other, we have added the errors in quadrature; they appear in the final column of Table 2. (In Figure 6 below we show these error bars, while subsequent figures show a more conservative generic error bar of ±0.10 dex.) We note that because these stars are all in the same cluster, the *relative* errors in the parameters and thus in the abundances are reduced.

4. Results

4.1. Temperature

Figure 6 shows the dependence of Be on stellar effective temperature. The dotted line at A(Be) = 1.42 indicates the Be abundance in meteorites (Anders & Grevesse 1989). This figures shows the

following: 1) The two hottest stars in our sample show little or no Be deficiency (and also show no Li deficiencies. 2) Stars in the region of the Li dip temperatures, 6400 - 6850 K, are depleted in Be as well as in Li. 3) Hyades stars that are cooler than about 5800 K have Be abundances that are near the value for meteorites, i.e. Be is undepleted.

The reality of the Be dip in the F stars (seen in Figure 6) is demonstrated in part in Figure 7 which shows the spectrum synthesis in vB 37 where T_{eff} = 6814 K. The solid line synthetic spectrum through the observed points (filled circles) is for A(Be) = 0.60, or 0.55 dex below solar Be, A(Be) = 1.15, shown by the dotted line. (It is 0.82 dex below meteoritic Be (A(Be) = 1.42).) The synthesis for essentially no Be (A(Be) = -3.00) is shown by the dashed-dotted line. These calculated spectra indicate that vB 37 does have Be and that it is deficient in Be relative to the sun, to meteorites, and to the cooler Hyades stars (see Figures 3b, 4, and 5).

The dependence of both Li and Be with T_{eff} can be seen in Figure 8. The Be scale is shown on the left y-axis and the Li scale is shown on the right y-axis. The scale size is the same and they are normalized to the meteoritic abundances of Li (3.31 dex) and Be (1.42 dex), both values from Anders and Grevesse (1989). The peak for Li is near 6200 K and it falls off to both hotter temperatures - the Li "gap" - and cooler temperatures, the well-known fall off of Li with decreasing temperature in the G dwarfs, as shown so clearly by Cayrel et al. (1984). (The Li abundance is about 2.85 dex between 6000 K and 6300 K from the larger sample of stars in, for example, Ryan and Deliyannis (1995); Figure 8 shows Li only for the stars for which we made Be observations.)

The Be-T_{eff} profile is quite different from that of Li. In the F dwarfs there is a Be "gap" but it is not as deep as the Li "gap." In the G dwarfs between 5400 K and 5800 K Be appears to be undepleted, near the meteoritic value. (The star vB 21 of García López et al. (1995) shows that Be may be a little depleted at T_{eff} = 5250 K.) To show the difference in the Li-T_{eff} profile and the Be-T_{eff} profile for the cooler stars, we have plotted only those stars with T_{eff} < 6400 K in Figure 9. The abundance of Li declines with temperature in the G stars from its peak (near 6300 K) by more than two orders of magnitude while Be is undepleted. The abundance of Be may show a small increase from 6300 K to its plateau value for the ten stars below 5750 K of A(Be) = 1.33 $\pm$0.06, near the meteoritic value. This indicates that the mixing is slowly depleting the surface Li while leaving the surface Be unchanged.

4.2. Rotation

In this section we focus on rotation as the mechanism of the slow mixing which causes the depletions of Li and Be in F and early G dwarfs. Other mechanisms such as diffusion, mass loss, gravity waves have been considered, discussed, and rejected in Stephens et al. (1997) and Deliyannis et al. (1998) in those papers about *both* Li deficiencies and Be deficiencies. We emphasize, though, the importance of refining previous theories and models and investigating additional mechanisms now that so much more high-quality data on Be is available.

Dr. C. Deliyannis has kindly provided a table of the points calculated in Deliyannis & Pinsonneault (1997) for simultaneous depletion of Li and Be due to rotationally-induced mixing, as seen in their Figure 2. These calculations were for ages of 100 Myr, 1.7 Gyr, and 4.0 Gyr at two initial rotational velocities, v(init) = 10 km s^{-1} and 30 km s^{-1}. We have interpolated linearly between those points for 100 Myr and 1.7 Gyr at the age of the Hyades of 800 Myr for both values of v(init). For v(init) of 30 km s^{-1} the calculations do not go below 5638 K. On the hot side, for v(init) = 10 km s^{-1} at age = 1.7 Gyr, the abundance of Be plummets from 6485 K to 6609 K which makes linear interpolation unrealistic and risky.

In Figure 10 we show our Be abundances on an expanded scale with the theoretical predictions from DP97, as interpolated to the Hyades age. These curves for the initial rotations of 10 and 30 km s^{-1} fit the observed Be abundances very well and seem to imply a spread in the initial rotation velocities.

We have done the same interpolation for the predicted Li depletion at the Hyades age. These results are shown in Figure 11. The match is not nearly as good, especially for the cooler stars. Since Li is more fragile than Be with respect to the destruction by nuclear reaction, it is more sensitive to the stellar model parameters than Be. There has been a careful study by Chaboyer, Demarque & Pinsonneault (1995) addressing Li in the Hyades specifically with models that included rotation and diffusion. Now that Be abundances are available, models which include both Li and Be should be made; the results from both elements can be used to constrain the models better.

Eight of our stars have had rotation periods determined by photometric variations (Lockwood et al. (1984), Radick et al. (1987), Radick et al. (1995)). The only connection appears to be that the cooler stars have longer rotation periods and less Li than the warmer stars. This could be the result of greater spin-down for the cooler stars accompanied by greater Li depletion. Rebolo & Beckman (1988) discuss this trend of increased Li depletion with longer rotation periods. *The Be abundance appears to be unaffected.* There are three stars near 6100 K (vB 31, 59, 65) with $P_{rot} \sim$ 5.5 days (and $<$A(Li)$>$ = 2.96) with a mean A(Be) = 1.20, three stars near 5800 K (vB 63, 64, 97) with $P_{rot} \sim$8.3 days (and $<$A(Li)$>$ = 2.49) with a mean A(Be) = 1.28, and two stars near 5450 K (vB 69, 92) with $P_{rot} \sim$10.3 days (and $<$A(Li)$>$ = 1.22) with a mean A(Be) = 1.28. All of these eight stars in these three temperature/rotation groups (6100 K, 5.5 d; 5800 K, 8.2 d; 5450 K, 10.5 d) have the same A(Be) of ∼1.25.

4.3. Simultaneous Depletion of Li and Be

For field stars in the temperature range of 5850 - 6680 K the abundances of Li and Be are correlated (Deliyannis et al. 1998 and Boesgaard et al. 2001). The temperature of 5850 K is near the cool end of the "Li peak" in the Hyades while 6680 K is in the center of the "Li dip" in the Hyades. The correlation in the field stars has a slope of 0.36, so when Li is decreased by a factor of 10, Be decrease by 2.2 times. This correlation is quite remarkable and covers field stars with a

range of ages and metallicities ([Fe/H] between −0.40 and +0.15).

We have 18 Hyades stars that fall in this temperature range. They have slightly higher metallicity than is typical of our field stars. Figure 12 indicates that the relation evinced by our Hyades data for 6680≥T_{eff}≥5850 K appears to be, within the uncertainties, identical to that of field stars of the same temperature from Boesgaard et al. (2001). Indeed, the ordinary least squares fit to the Hyades data gives

A(Be)=0.413(±0.058)-0.084(±0.157)

whereas that for the field star data is

A(Be)=0.359(±0.037)+0.146(±0.097).

While the correlated Be-Li depletion relation defined by Figure 12 appears to be tight, we searched for any trends in the residuals of the data points about the fitting lines given above. Figure 13 shows the Δ A(Be) residuals (observed Be minus the fitted value) versus the effective temperature. The residuals do appear to demonstrate a slight trend with T_{eff} in the sense that the cooler stars deplete slightly less Be with respect to Li than do the hotter stars at the level of one or two tenths of a dex. The ordinary correlation coefficient of the combined sample is not huge (−0.48; likely indicating that observational scatter is also an important source of the modest scatter in Figure 12), but is still statistically significant at the 99.8% confidence level. We have no reason to believe this is an artifact of our analysis.

The slope for the cooler stars alone is 0.26 while for the hot stars alone it is 0.40. So as Li decreases by ten times, Be decreases by 2.5 times for the hot stars and by 1.8 times in the cooler stars. As indicated by the theory of rotational mixing (e.g. DP97, Chaboyer et al. 1995), the cooler stars with deeper convections zones deplete more Li relative to Be than do the hotter stars. Additional data for a larger sample may better define the trend, if real.

For the field stars, with a range of age and metallicity, we have shown that the Li and Be depletions are correlated. Our stars in the Hyades have the same metallicity and the same age – a relatively young age of 8 x 10^8 yr. This would seem to indicate that the depletions of Be and Li are occurring simultaneously since both are down in a cluster of young stars. This hypothesis will be tested by our studies of Be in other star clusters.

4.4. Initial Be Abundance

The abundance of Be found in the Sun by Chmielewski, Brault & Müller (1975) is 1.15 dex while the meteoritic abundance at 1.42 dex is a factor of two higher (Anders & Grevesse 1989). It had often been suggested that this difference is due to the incompleteness of the sources of opacity in the ultraviolet. Balachandran & Bell (1998) studied the O abundance in the sun from the OH lines in the IR and in the UV and conclude that the UV opacity has to be increased in order for

the O abundance in the UV agree with that in the IR. They derive an empirical enhancement of a factor of 1.6 in the UV opacity. When they apply this enhancement to solar Be they find an agreement between the meteoritic Be and the solar photospheric abundance. In other words, they suggest that Be is undepleted in the Sun.

Our Hyades stars provide an opportunity to examine Be depletions in solar-type stars. There are ten Hyades stars in our sample with $T_{\rm eff}$ in the range of 5430 to 5750 K. These stars have little or no Be depletion (see Figures 6 and 9) with a range in A(Be) of 1.25 - 1.41 and a mean A(Be) = 1.33 ±0.06. According to Balachandran & Bell (1998), the meteoritic abundance of 1.42 with the Holweger & Müller (1974) solar model corresponds to 1.40 in the Kurucz models that we use. This is similar to our mean within the errors. We note that with the same instrument, the same data reduction process, the same analysis, and the same line list, we find the solar abundance to be A(Be) = 1.15 dex (see section 3.2). These solar-type Hyades stars clearly have more Be than the Sun–presumably either because they have not depleted as much Be and/or because their initial Be abundance was higher.

We note that the models of Deliyannis & Pinsonneault (1997) use the value of A(Be) = 1.42 as the initial Be abundance. Their isochrone for 1.7 Gyr shows that Be has been depleted. Our interpolations, shown in Figure 10, indicate that there has been some Be depletion by the Hyades age, perhaps by 0.1 to 0.2 dex for the cool stars. We could use the models as a guide here to conclude that Be depletion has occurred, but only if the Hyades initial abundance were comparable to or larger than the meteoritic value. We refrain from drawing this conclusion, however, in part because the models we used here do not work as well in matching the Li depletions (see Figure 11); the models of Chaboyer, Demarque and Pinsonneault (1995) do show a good match to the Hyades Li abundances with rotation and diffusion, but do not include Be yet. Whether or not the Hyades stars are depleted, the differential comparison with the Sun shows that the Hyades A(Be) is larger than solar. We know that the Hyades is more metal-rich than the Sun by 0.13 dex (Boesgaard 1989 and Boesgaard & Friel 1990) and might have a larger initial Be abundance also. This could result from a greater amount of Be in the region of the Galactic disk where the Hyades were formed at a much later time than the formation of the Sun and the meteorites. We do not know the initial Be abundance for the Hyades and there is lingering uncertainty about the UV opacity; thus we are unable to conclusively demonstrate the reality of the implied ∼0.1 dex Be depletion.

In Figure 8 we have plotted Li abundances only for the stars for which we have observed Be. The larger sample of stars with Li abundances (about twice as many) shows that the "Li peak" between about 6000 - 6300 K is at about A(Li) = 2.85 dex (see, for example, Ryan & Deliyannis 1995). That is to say that Li is indeed more depleted than Be from their respective meteoritic values: about 0.45 dex for Li and about 0.25 dex for Be. This is the prediction of slow mixing caused by rotation. Stars in this temperature range do fit the Li and Be depletion pattern of Figure 12.

One final point on this issue can be seen by the trend in Figure 13 of ΔBe with temperature;

this trend would be in the opposite sense if we were missing UV opacity. IN addition, it seems clear that the cooler Hyades stars do **not** have lower Be abundances than the two stars on the hot side of the Be dip; if deficient opacities were a problem, then the cooler stars would have lower A(Be) than the hotter stars.

4.5. The Ratio of Li/Be

There are several Hyades stars that appear to be undepleted in their Li abundances. Stars which are undepleted in Li are expected to be undepleted in Be since Be is less likely to be destroyed by nuclear reactions than Li; it takes a higher temperature – which occurs in deeper layers of the stellar interior – to destroy Be than Li. There are 11 stars in our sample which have A(Li) > 2.8. For these 11 stars A(Li)/A(Be) is 1.86 $\pm$0.17 which gives N(Li/Be) = 72. For the eight stars with A(Li) > 3.0 the value of A(Li)/A(Be) is 1.92 $\pm$0.16 and N(Li/Be) = 83. Those eight stars can be thought to be representative of the initial Li. The ten coolest stars may give a better value for initial Be because they are all slow rotators and therefore the synthesis gives a more accurate Be abundance. In that case, A(Li) $-$ A(Be) = 3.146 $-$ 1.326 = 1.820 for N(Li/Be) = 66. We can conclude that the material that formed the Hyades cluster had a ratio of Li/Be of 75 $\pm$30. We note that the solar system (meteoritic) Li/Be ratio is 77.6, in excellent agreement with the Hyades stars.

5. Summary and Conclusions

High-resolution ultraviolet spectra were obtained with Keck I and HIRES of 34 F and G dwarfs in the Hyades. The median signal-to-noise ratios of these spectra is 88 and 80% have S/N > 70. We have made model atmospheres for each star from the stellar parameters and found Be abundances from spectrum synthesis.

There is strong evidence of a *Be dip in the F stars* shown in Figures 6 and 8. In the middle of the Be dip ($T_{\rm eff}$ $\sim$6700-6800 K), the Be abundance is reduced to A(Be) = 0.60 which is down from the mean from the G stars of 0.73 dex or by a factor of $\sim$5. In this region Li is depleted by a factor of at least 30 and probably more than 100. There appears to be *little or no depletion of Be in the G stars*. This was shown in Figures 6, 8, and 9 where the Be abundances are plotted against temperature. The rotationally-induced mixing models of Deliyannis & Pinsonneault (1997) (which we interpolated to the age of the Hyades) provide predicted Be abundances. These are a good match to the derived Be abundances within the error bars and the range in initial rotation that might be expected. The match for Li is less good, particularly at the cooler temperatures; the work of Chaboyer et al. (1995), aimed specifically at Li in clusters, does give a good match for Li by including additional mixing mechanisms. This type of calculation should now be expanded to encompass the Be results.

For the ten stars cooler than T_{eff} = 5800 K there appears to be little or no depletion of Be and the values of A(Be) are near the level found in meteorites where A(Be) = 1.42 (Anders & Grevesse 1989); the mean value of A(Be) for those 10 stars is 1.33 $\pm$0.06. The Be abundance derived for the Sun by us from our Keck spectrum is A(Be) = 1.15 dex in agreement with the value of 1.15 found from the detailed study by Chmielewski, Brault & Müller (1975). This indicates that the solar-type Hyades stars have more Be than the Sun and may imply that the Sun has depleted some of its Be during its lifetime. Given present uncertainties we can not, on the basis of current data, distinguish between this and the alternative possibility that the UV opacities used in our synthesis are in error and that the initial Hyades Be abundance was larger than meteoritic.

For the eight stars which apparently have undepleted Li (A(Li) $>$ 3.0) we find that Be is also apparently undepleted and that the Li/Be ratio is 75 $\pm$30.

The Li and Be abundances are correlated for the stars in the temperature range of 5850 K (near the Li abundance peak in the Hyades) and 6680 K (at the bottom of the Li gap in the Hyades). This was shown in Figure 12 where the Hyades results were superposed on the field star results. The field star results have been shown to follow the predictions of models of slow mixing caused by rotation. Our Hyades results indicate that the Li and Be abundances are not just correlated, but they are occurring together. Theoretical models of light element depletion can now be further refined to include these new results on Be in the Hyades open cluster.

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Table 1. Log of the Observations

vB No.	Other ID	Spectral Type	V	B-V	Night (UT)	Exp (min)	S/N
9	BD+19 641	G4V	8.66	0.708	1999 Nov 14	50	71
10	HD 25825	G0	7.82	0.589	1999 Nov 14	25	88
13	HD 26345	F6V	6.62	0.385	2001 Feb 01	10	51
14	HD 26462	F4V	5.71	0.327	2001 Feb 01	7	99
15	HD 26736	G3V	8.09	0.658	1999 Nov 13	40	61
17	HD 26756	G5V	9.16	0.696	1999 Nov 13	60	95
19	HD 26784	F8V	7.11	0.47	1999 Nov 15	13	106
27	HD 27282	G8V	8.46	0.715	1999 Nov 13	60	100
31	HD 27406	G0V	7.47	0.566	1999 Nov 15	20	99
37	HD 27561	F5V	6.61	0.380	2001 Feb 01	12	46
38	HD 27628	A3m	5.72	0.298	2001 Feb 01	7	31
48	HD 27808	F8V	7.13	0.521	2001 Feb 01	18	18
59	HD 28034	G0	7.47	0.543	1999 Nov 15	18	97
61	HD 28069	F7V	7.36	0.470	2001 Feb 01	20	76
62	HD 28033	F8V	7.35	0.537	1994 Oct 27	25	116
63	HD 28068	G1V	8.05	0.632	1999 Nov 14	35	92
64	HD 28099	G6V	8.12	0.657	1999 Nov 13	45	114
65	HD 28205	F8V	7.42	0.535	1999 Nov 15	18	89
66	HD 28237	F8	7.49	0.555	1994 Oct 27	30	107
69	HD 28291	G5	8.64	0.746	1999 Nov 15	50	88
77	HD 28394	F7V	7.01	0.47	1999 Nov 14	18	75
78	HD 28406	F6	6.90	0.43	1999 Nov 14	14	85
81	HD 28483	F5	7.10	0.47	1999 Nov 14	14	93
86	HD 28608	F5	7.04	0.437	1999 Nov 14	14	86
87	HD 28593	G8V	8.58	0.743	1999 Nov 13	60	89
92	HD 28805	G8V	8.66	0.741	1999 Nov 13	60	69
97	HD 28992	G1V	7.94	0.634	1999 Nov 15	30	76
101	HD 29225	F8	6.64	0.407	2001 Feb 01	12	59
106	HD 29461	G5	7.94	0.669	1999 Nov 14	40	95
113	HD 30311	F5	7.26	0.549	1999 Nov 15	15	59
114	HD 30355	G0	8.52	0.723	1999 Nov 15	55	100
121	HD 30738	F8	7.27	0.480	2001 Feb 01	20	84
124	HD 30869	F5	6.26	0.462	1999 Nov 13	14	104
128	HD 31845	F5V	6.76	0.418	1999 Nov 14	18	88

Table 2. Atmospheric Parameters and Abundances

Star vB	$T_{\rm eff}$ (K)	$\log g$	ξ (km s^{-1})	v sin i (km s^{-1})	A(Li)	Ref.[a]	A(Be)	σ
9	5538	4.44	1.06	...	<0.79	T	1.25	0.05
10	5982	4.39	1.27	...	2.76	T	1.08	0.05
13	6725	4.32	1.60	18	<1.78	B	0.61	0.10
14	7042	4.29	1.74	≤12	3.43	B	1.25	0.07
15	5729	4.42	1.15	...	2.29	T	1.30	0.05
17	5598	4.43	1.10	...	1.99	T	1.39	0.05
19	6300	4.35	1.42	≤12	3.01	B	1.04	0.09
27	5535	4.44	1.04	...	1.61	T	1.38	0.05
31	6071	4.39	1.30	10	2.96	T	1.25	0.05
37	6814	4.31	1.64	12	2.29	B	0.60	0.08
38	7376	4.28	1.86	15	3.03	B	1.18	0.10
48	6246	4.37	1.38	≤12	3.04	B	1.28	0.09
59	6120	4.38	1.32	≤6	2.86	B	1.14	0.06
61	6260	4.35	1.41	18	3.18	B	1.20	0.10
62	6185	4.37	1.36	5	3.14	B	1.15	0.05
63	5822	4.41	1.19	...	2.51	T	1.26	0.05
64	5732	4.42	1.15	...	2.32	T	1.41	0.05
65	6200	4.37	1.36	9	3.07	B	1.20	0.06
66	6204	4.38	1.35	8	2.78	T	1.11	0.06
69	5435	4.45	1.02	...	1.13	T	1.30	0.05
77	6330	4.35	1.24	25	2.46	B	0.98	0.10
78	6510	4.33	1.52	20	2.61	B	0.85	0.10
81	6470	4.35	1.48	18	2.24	B	0.92	0.10
86	6485	4.34	1.50	20	2.40	B	0.82	0.10
87	5445	4.45	1.04	...	1.18	T	1.26	0.05
92	5451	4.45	1.02	...	1.30	T	1.26	0.06
97	5814	4.41	1.19	...	2.64	T	1.17	0.05
101	6635	4.33	1.56	40	<1.16	B	0.55	0.21
106	5690	4.42	1.14	...	2.42	T	1.33	0.05
113	6139	4.38	1.33	7	2.84	T	1.15	0.06
114	5509	4.45	1.04	7	1.70	T	1.38	0.05
121	6337	4.35	1.44	12	3.27	B	1.25	0.07
124	6630	4.35	1.53	25	2.06	B	0.70	0.10
128	6560	4.32	1.55	25	2.25	B	0.90	0.10

References. — B = Boesgaard & Tripicco (1986) and Boesgaard & Budge (1998); T = Thorburn et al. (1993)

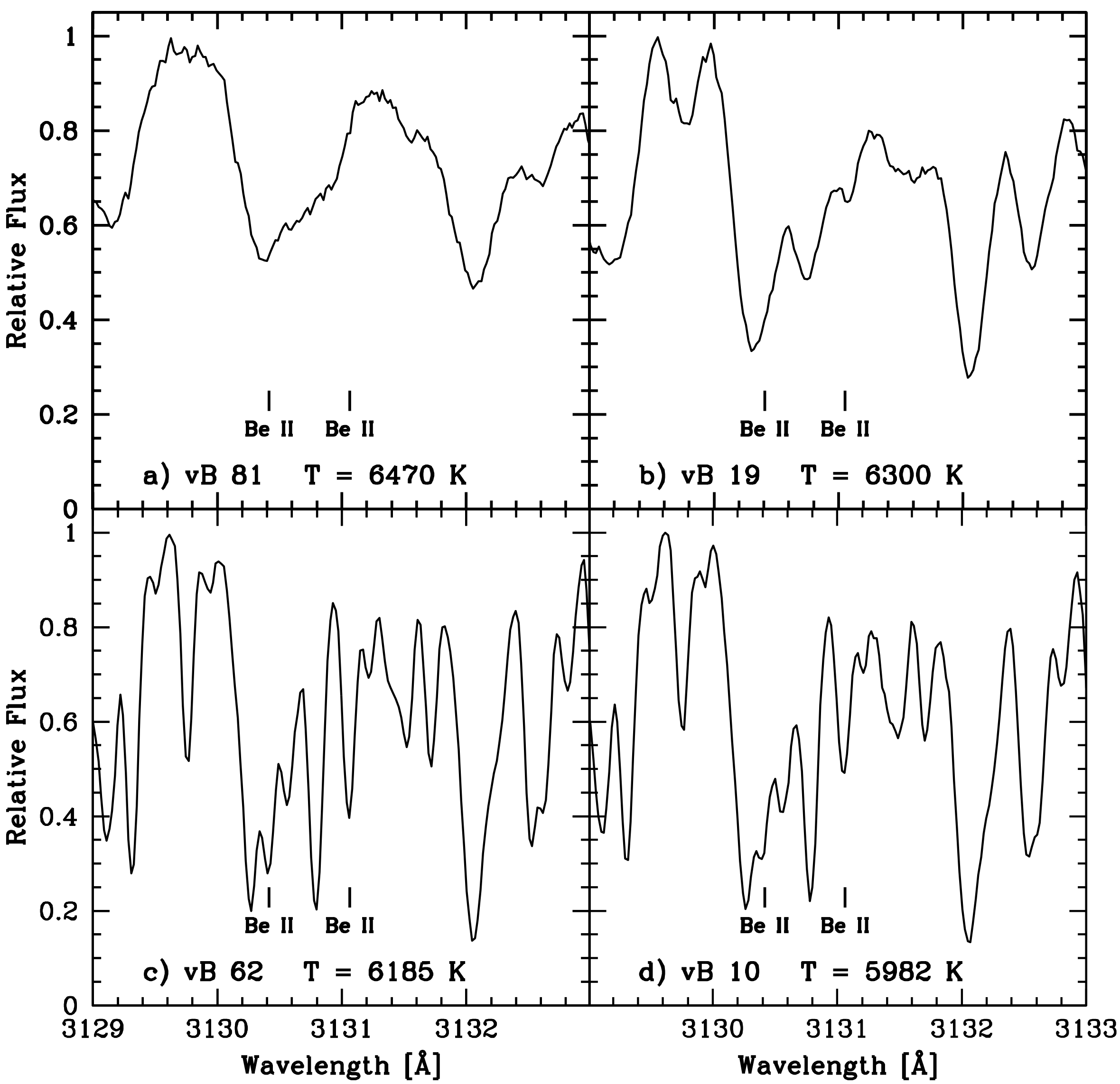

Fig. 1.— Examples of the Be II region of the spectra of some of the hotter Hyades stars. The positions of the Be II resonance lines are marked.

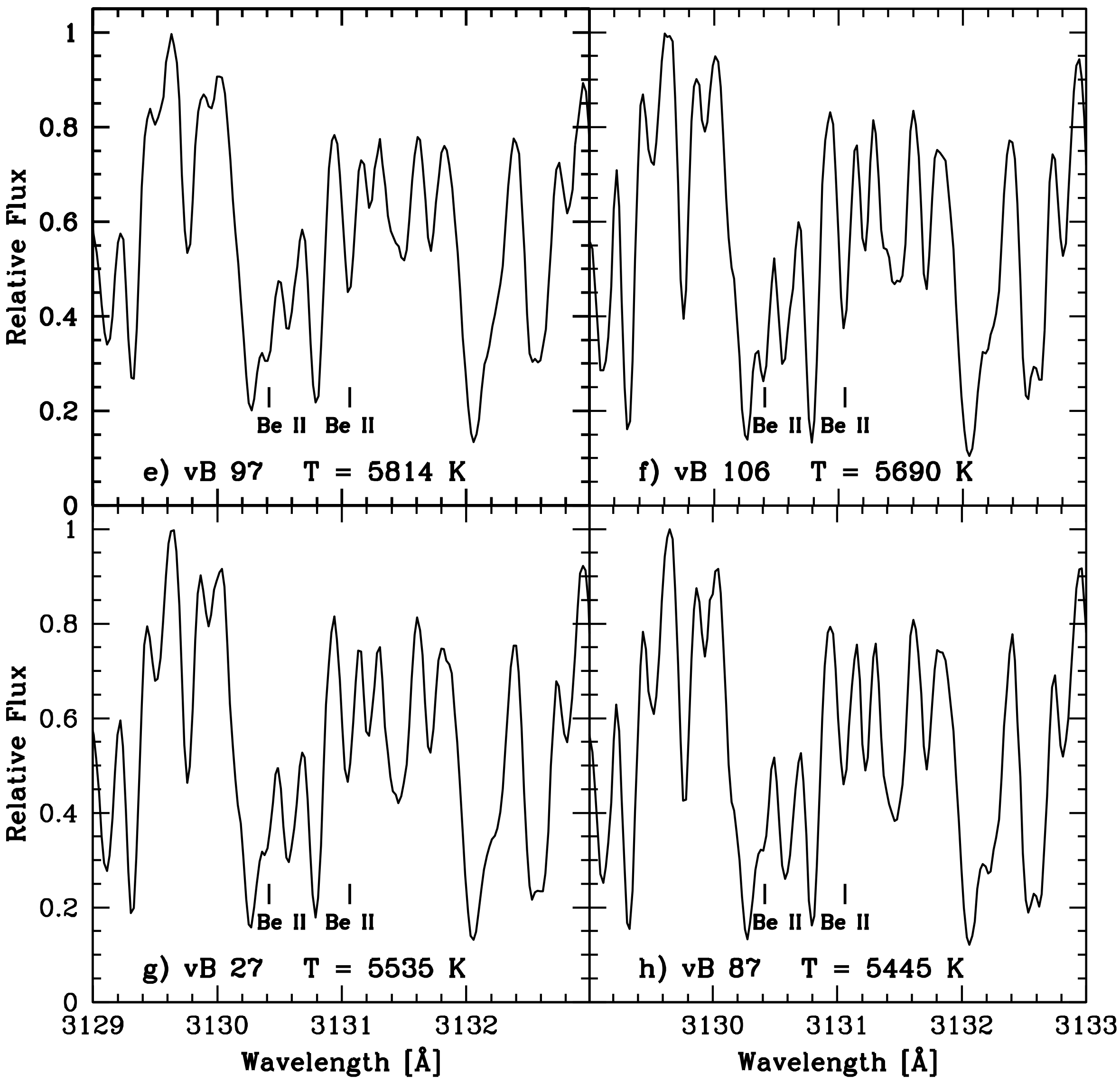

Fig. 2.— Examples of the Be II region in the spectra of some of the cooler Hyades stars.

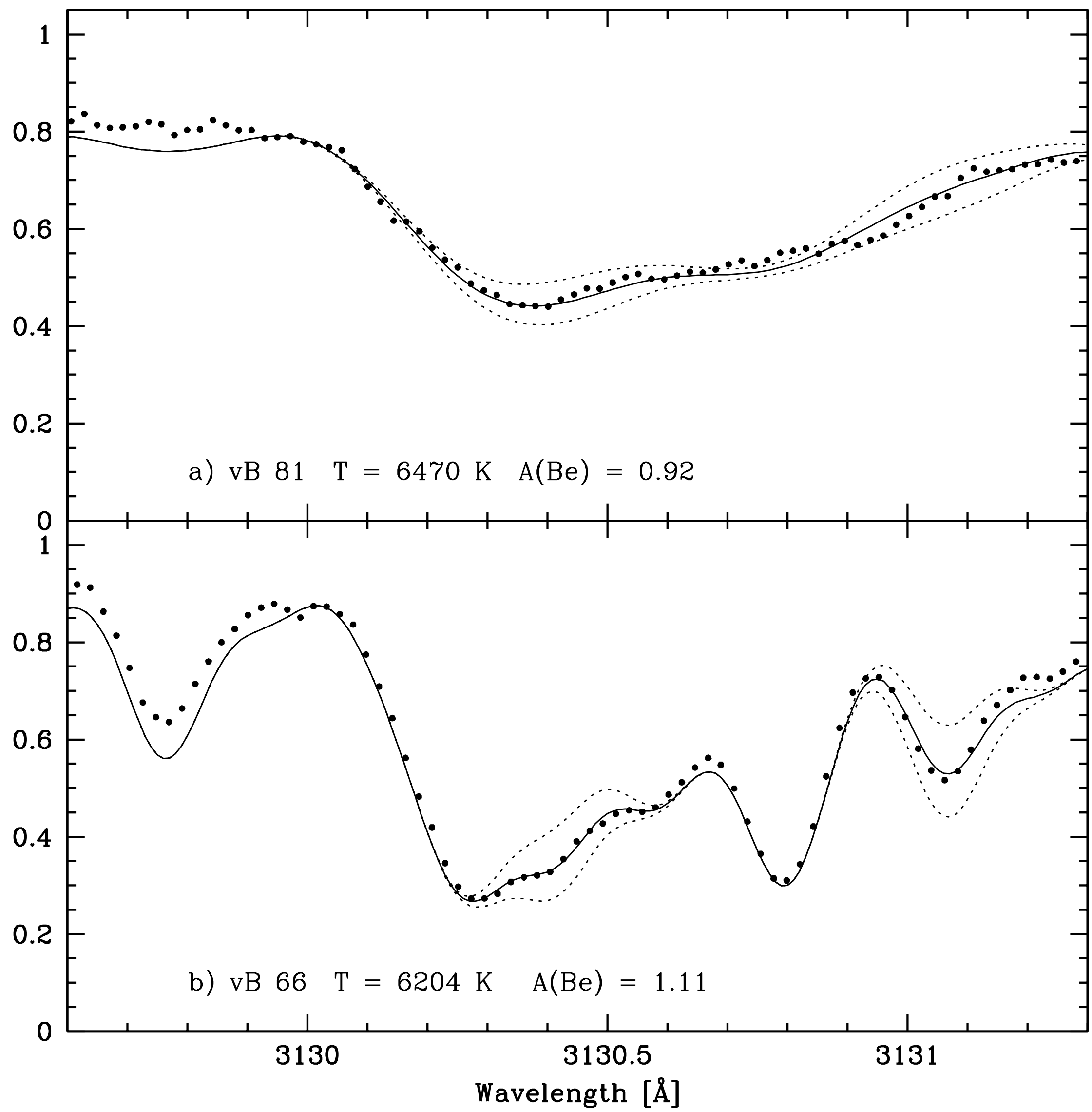

Fig. 3.— The spectrum synthesis fits for two of the hotter stars in the sample. The points are the observed spectrum; the solid line is the best fit and the two dotted lines represent Be abundances that are a factor of two larger and smaller than the best fit. The best fit value for A(Be) is indicated in the panel label. vB 81 is rotationally broadened with v sin i = 18 km s^{-1}, but the difficulty this causes in fitting the spectrum is somewhat offset by the fact that Be affects nearly the entire profile from 3130.15 to 3131.3 Å.

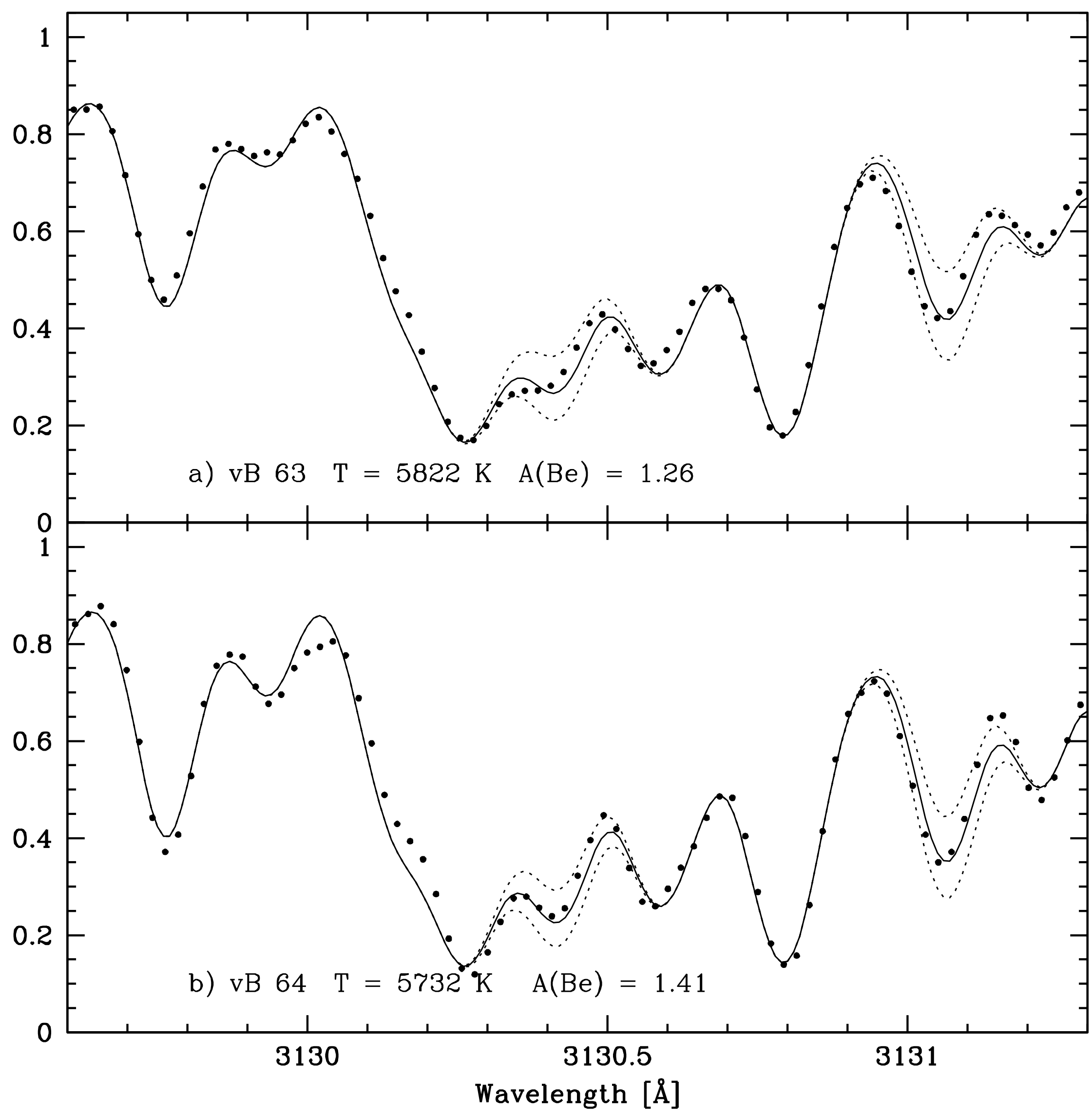

Fig. 4.— The spectrum synthesis fits for two of the intermediate temperature stars in our sample. The lines and symbols are as in Figure 3.

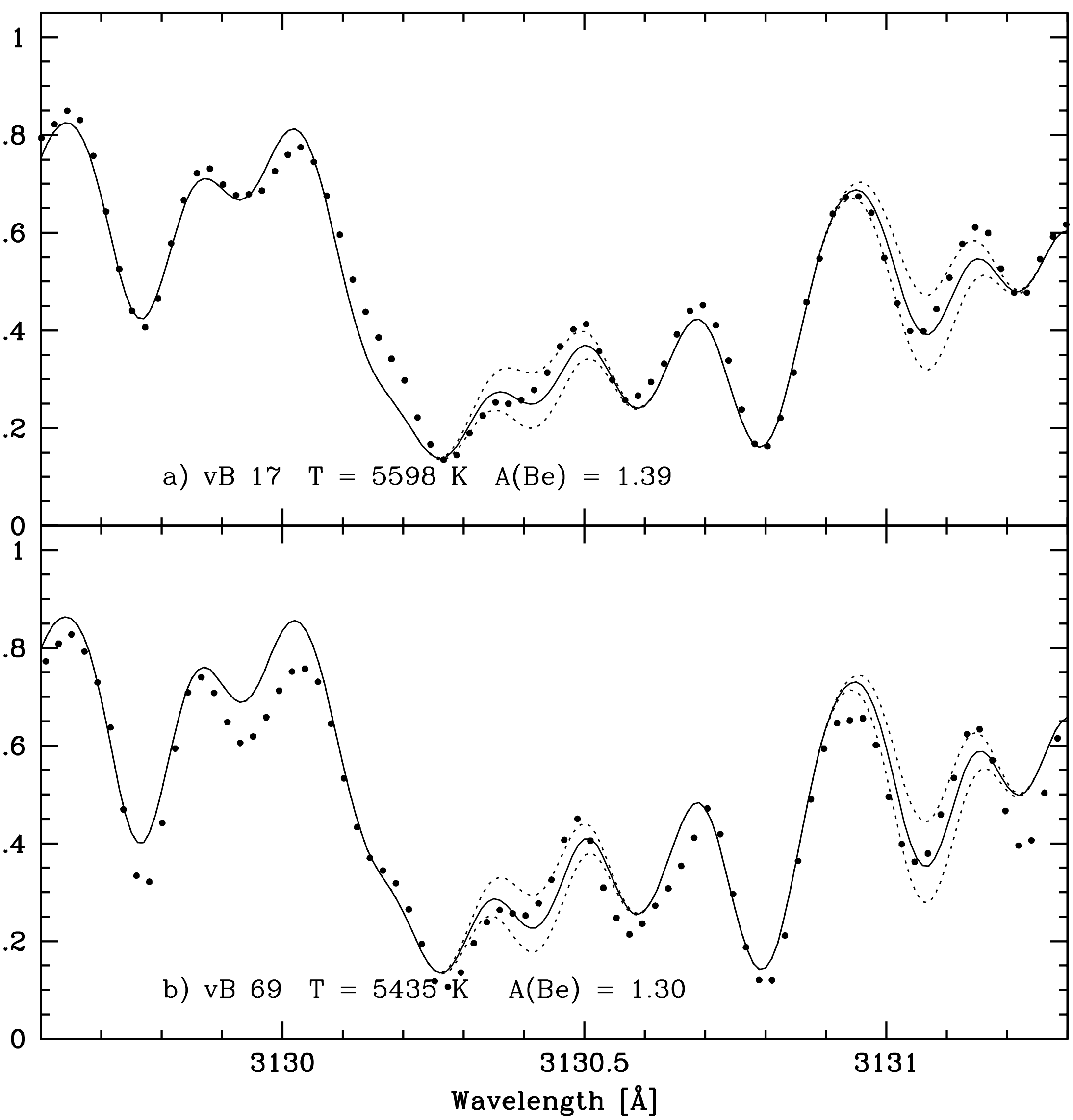

Fig. 5.— The spectrum synthesis fits for two of the cooler stars. The lines and symbols are as in Figure 3.

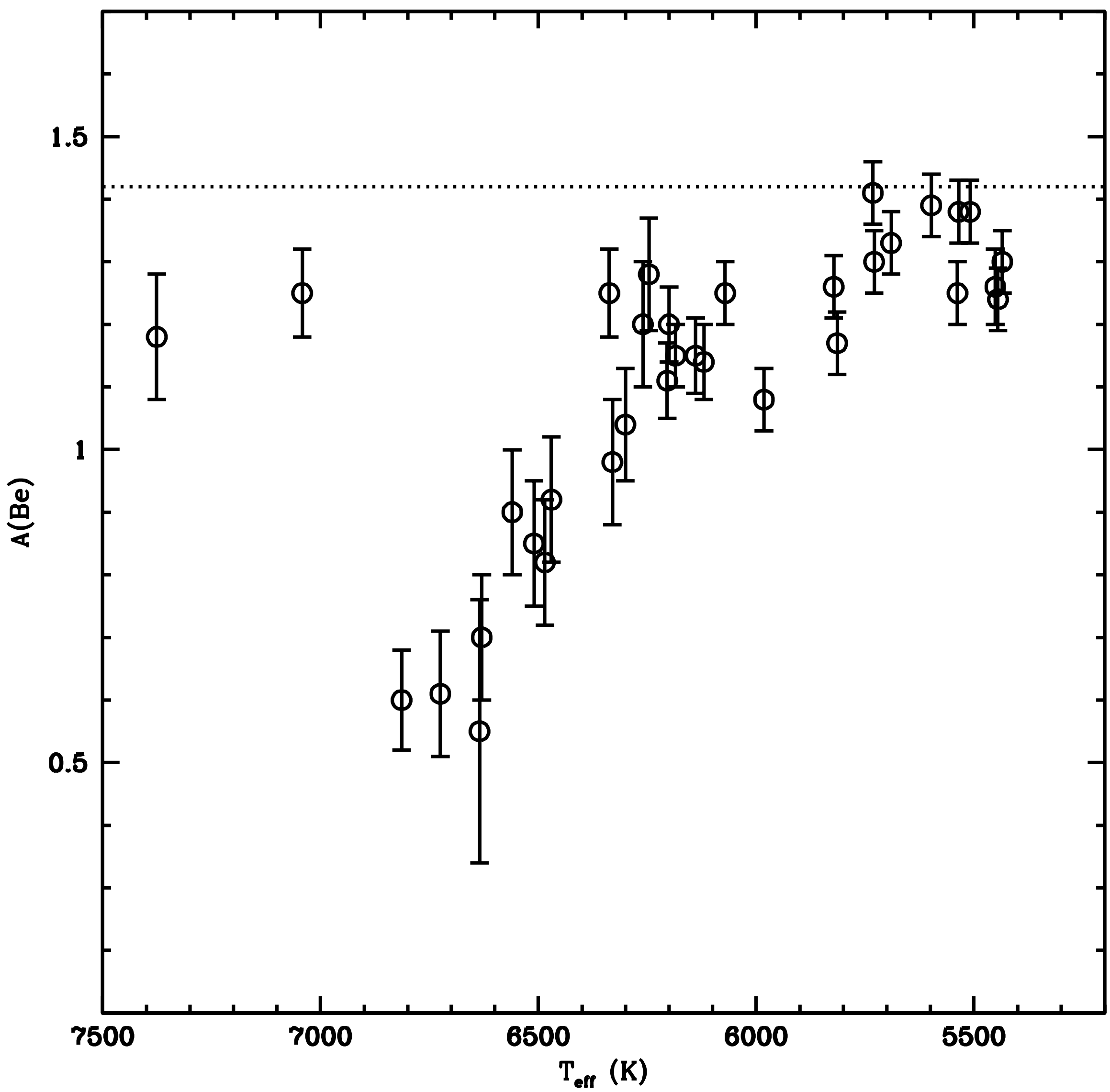

Fig. 6.— The derived Be abundances for our Hyades sample plotted against stellar effective temperature. The mid-F star Li dip is clearly seen in the Be abundances. Two stars on the hot side of the dip have approximately normal Be. In the cooler G stars there is no counterpart in Be to the precipitous drop in Li abundances with decreasing effective temperatures.

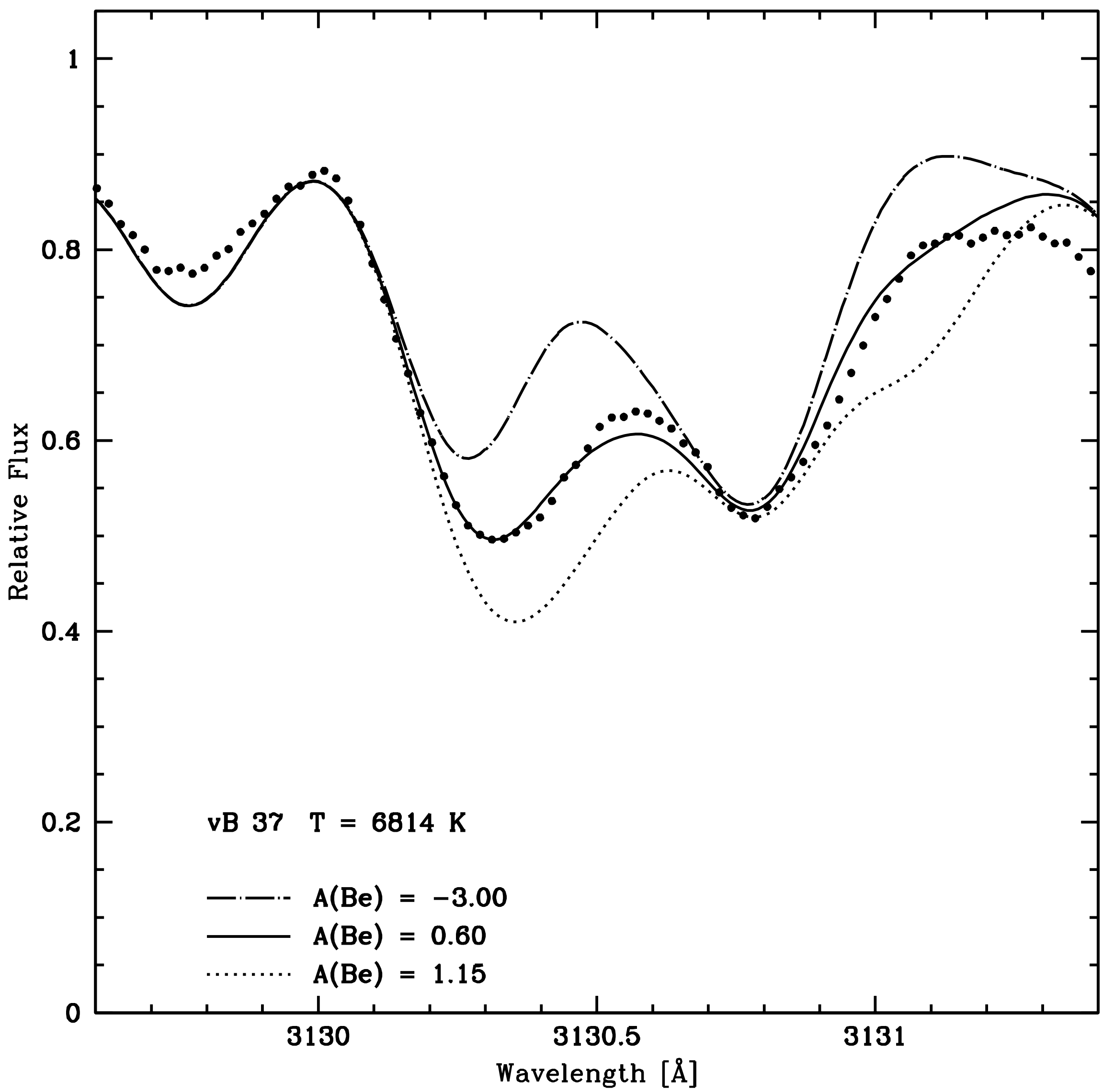

Fig. 7.— The Be synthesis of vB 37. This star is in the Be dip in Figure 6 (6814 K, 0.60). The observed spectrum is represented by the filled circles. The best fit Be abundance is A(Be) = 0.60, the solid line. This star has v sin i = 12 km s^{-1}, which rotationally broadens the blend containing the Be doublet. The dotted line with solar Be content, A(Be) = 1.15, clearly does not match the observed spectrum and shows the reality of the Be deficiency. The dashed-dotted line shows essentially no Be (A(Be) = −3.00) and this does not fit the observations either.

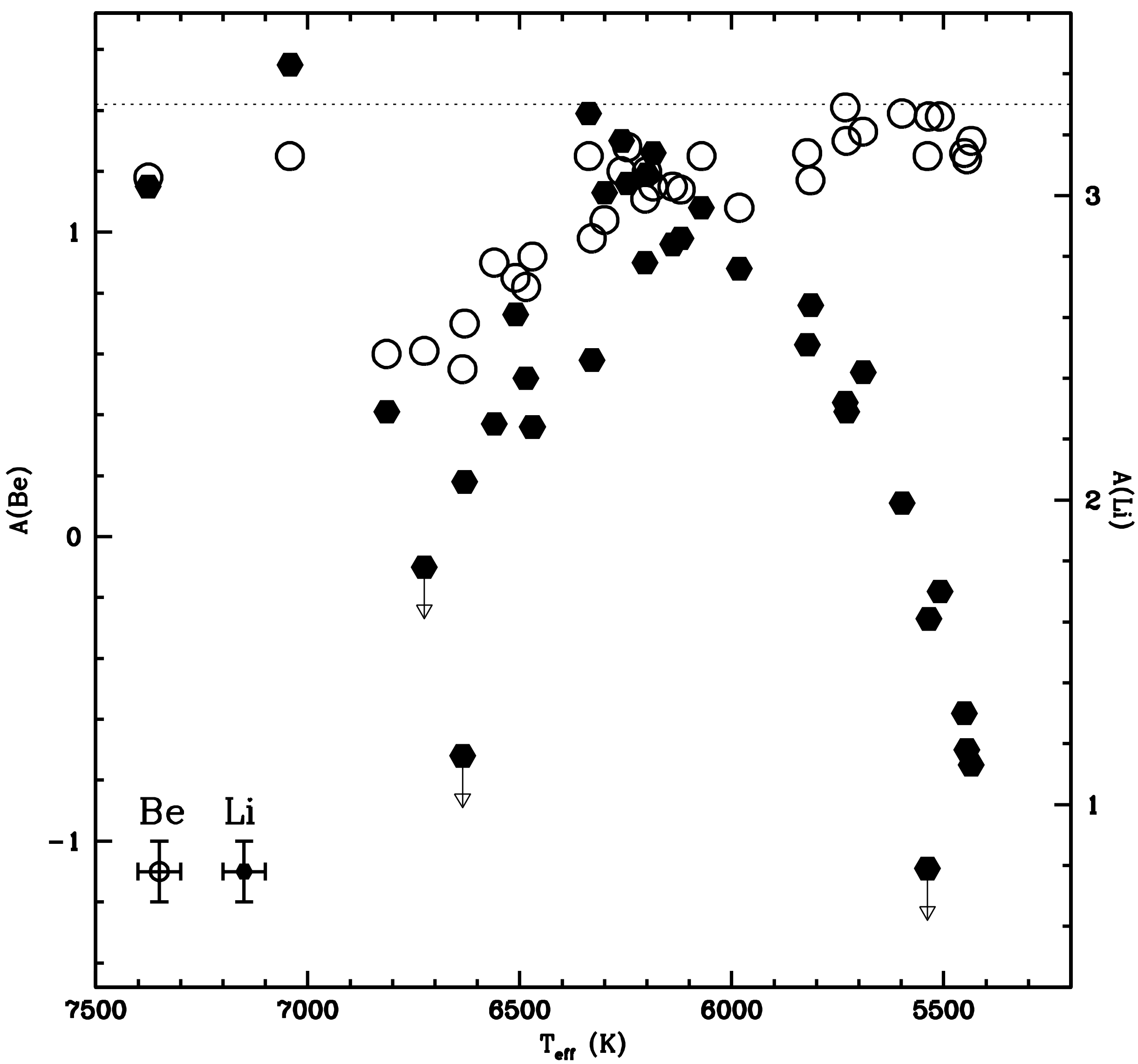

Fig. 8.— The abundances of Be, A(Be), and Li, A(Li), as a function of effective temperature. The open circles are the Be data points with the scale for A(Be) given on the left y-axis, while the Li data points are the solid hexagons with the y-axis labelled on the right. The lowest Li point at (5538, 0.79) represents an upper limit on A(Li). Typical error bars for Be and Li are shown in the lower left.

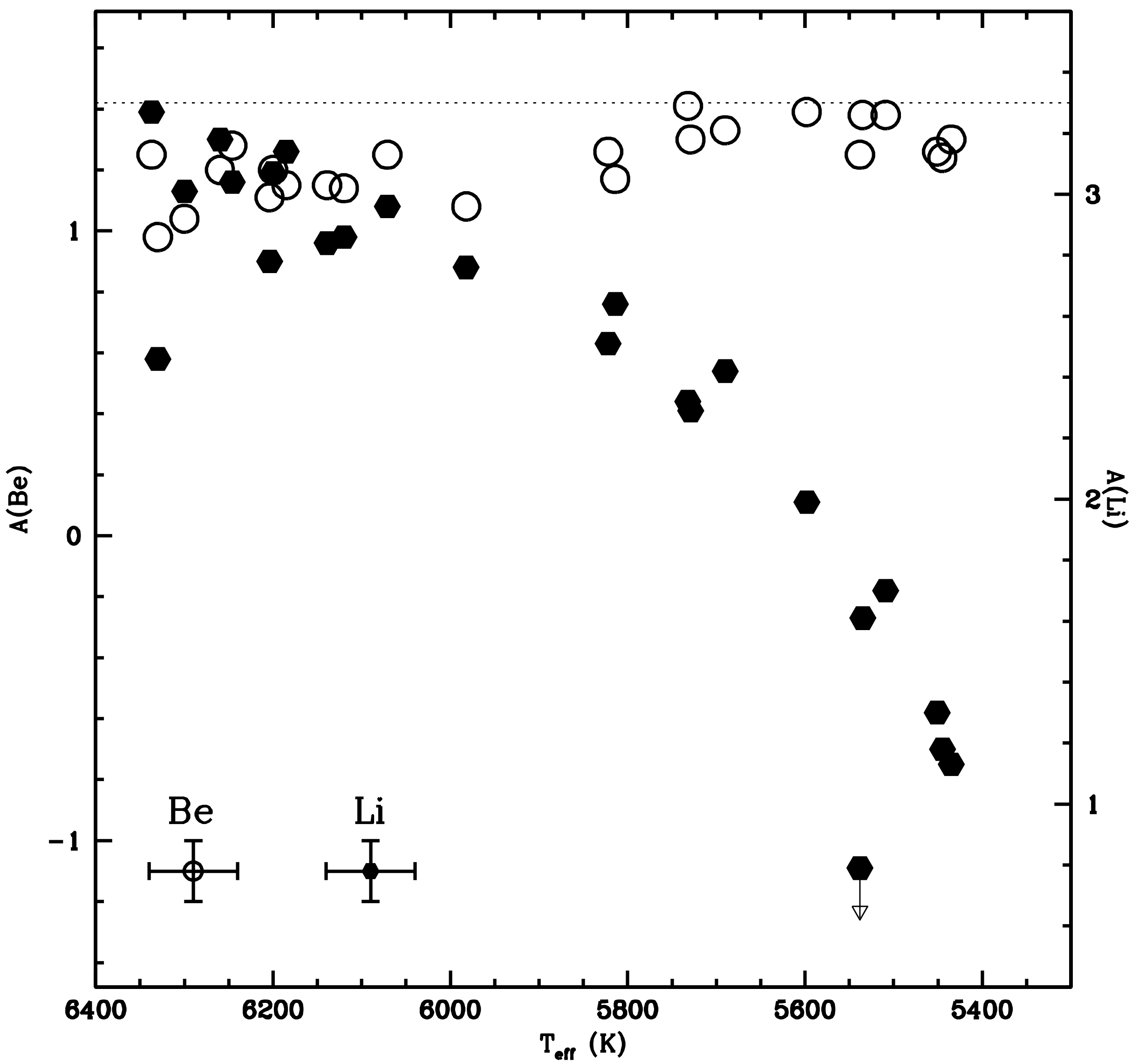

Fig. 9.— The abundances of Li and Be in the late F and G stars in the Hyades. The symbols and axes are as in Figure 8. This plot shows clearly that the decline in Li abundances with deepening convection zones in cooler stars is not present in the Be abundances.

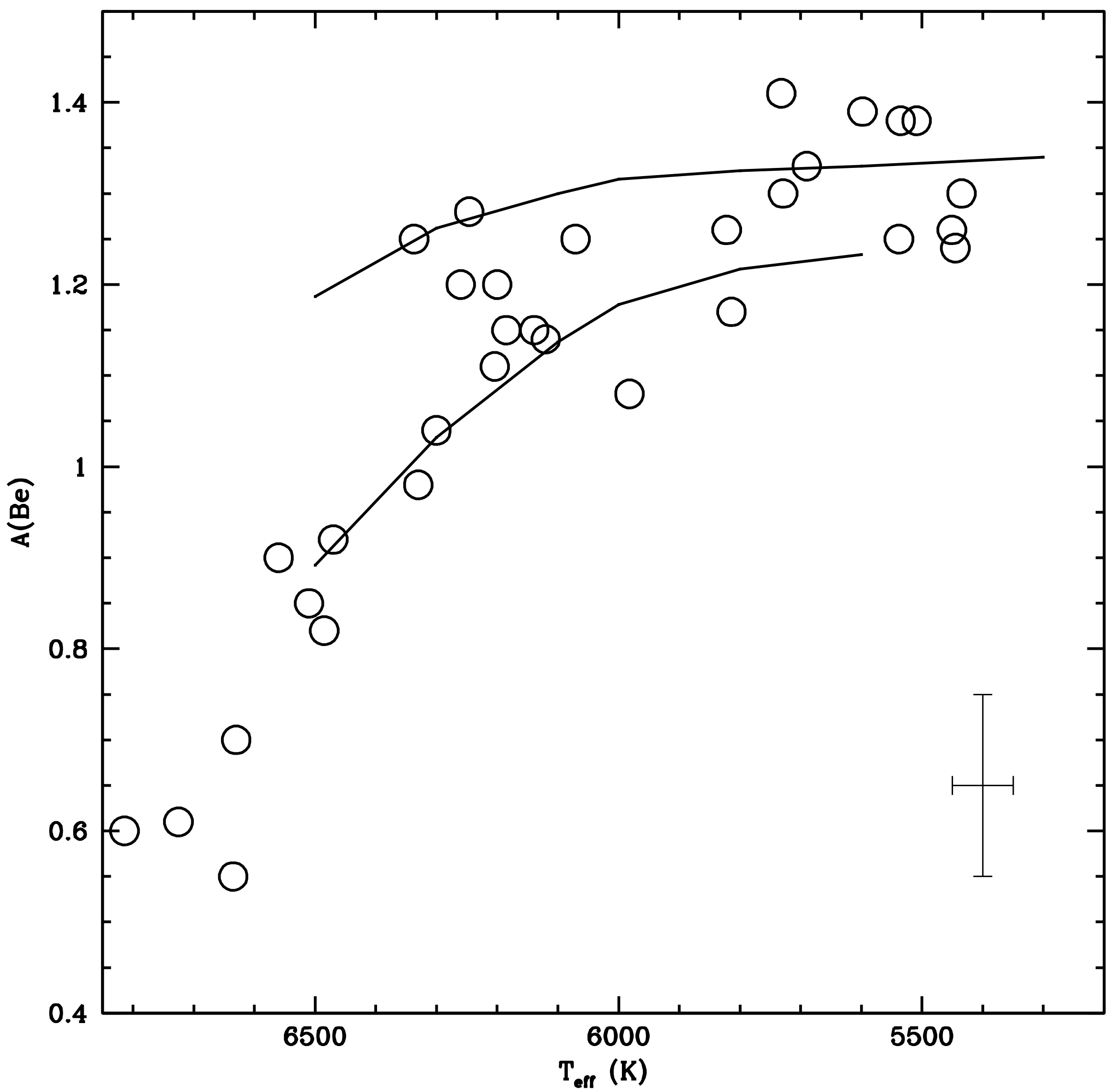

Fig. 10.— The Be abundances as a function of temperature along with the predictions of rotationally-induced mixing of Deliyannis and Pinsonneault (1997) as interpolated for the age of the Hyades at 800 Myr. The upper curve is for an initial rotational velocity of 10 km s^{-1} and the lower curve is for 30 km s^{-1}. The predictions are a good match for the data.

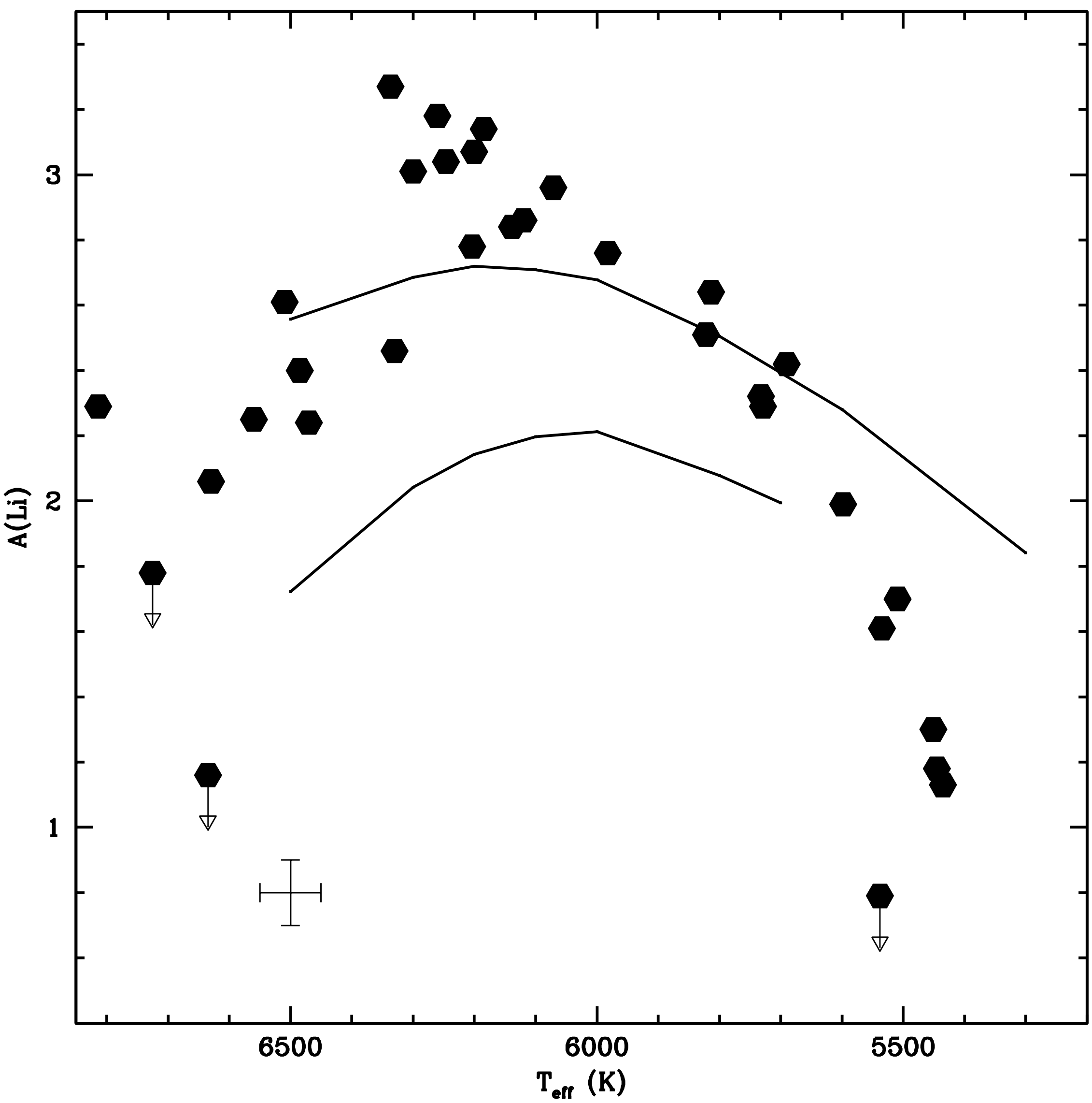

Fig. 11.— The Li abundances as a function of temperature with the predictions as in Figure 7. The predictions do not match the Li data as well as they do the Be data. The observed Li abundances at the Li "peak" are greater than those predicted and the fall off to both hotter and cooler temperatures are steeper than predicted.

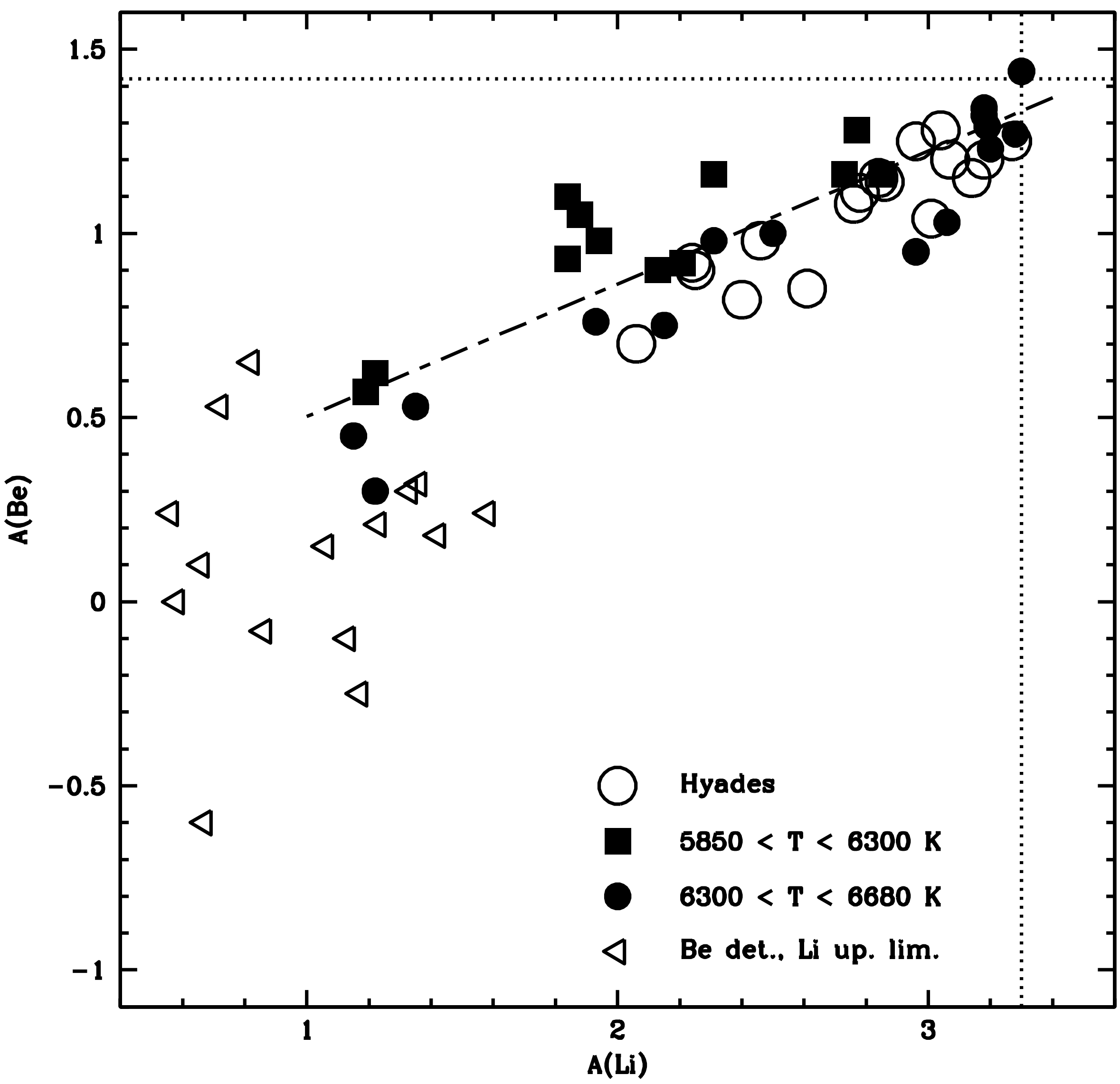

Fig. 12.— The correlation of Li and Be as found in Boesgaard et al. (2001) for field stars is also seen for the Hyades stars in this same temperature range, 5850 - 6680 K.

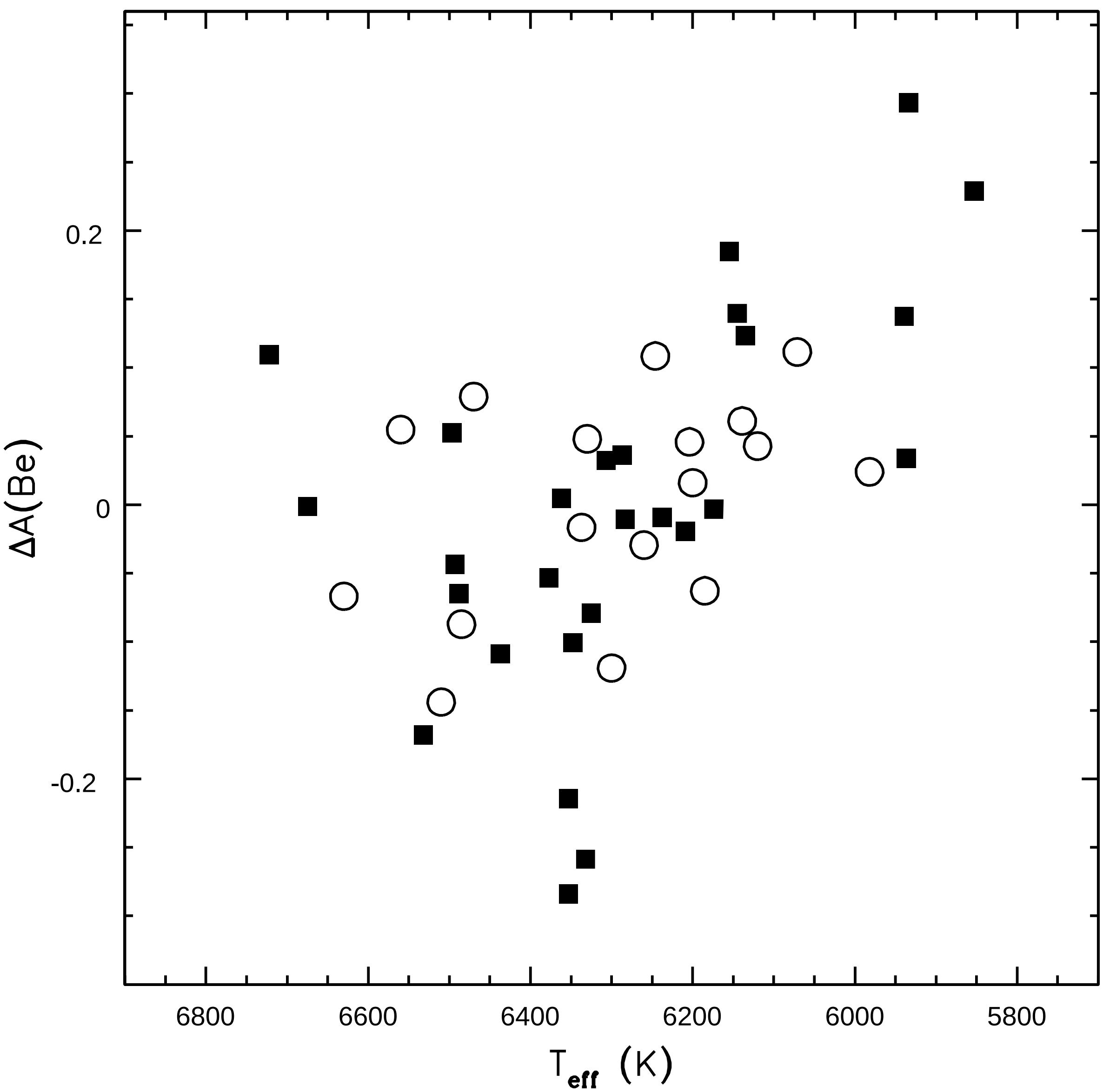

Fig. 13.— The Be abundance residuals (observed minus fitted) from the Be-Li relations for field stars (solid squares) and Hyades stars (open circles) versus effective temperature. A modest, but statistically significant, trend is found.